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Richard S. Allen, et al

Air Force Cambridge Research Laboratories
Hanscom Air Force Base, Massachusetts

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RICHARD S. ALLEN
JEAN M. CONNELLY
ROBERT VESPRINI

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A model is presented for the thickness of the electron density profile in the region above the F layer maximum. The model varies with time and solar conditions; it is specified by observations or predictions of the height of the F layer maximum; and it is independent of latitude. Results indicate that a mean thickness parameter can be estimated to within about 15 percent and that there is a useful reduction in the day to day variability. The model will be used in procedures to correct for ionospheric refraction effects to radar and satellite navigation systems.

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Contents

Illustrations

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Tables

Specification of the Thickness of the Topside of the Ionosphere

1. INTRODUCTION

The electron density of the upper ionosphere is usually modeled by empirical profiles that decrease monotonically with height. The calculated values of electron density are critically dependent on the initial choice of a thickness parameter for the interval just above the peak of the F2 region. Since there are so few field observations, it is common practice to equate the thickness of the top and the bottom of the F2 region and then to refer to climatological sources, such as those given by Barghausen et al[1] or CCIR[2] to obtain an estimate of a topside thickness parameter. Unfortunately, few climatological descriptions of the thickness of the lower ionosphere are based on detailed electron density profiles.

In this paper, another approach is suggested: To obtain an estimate of the height of the maximum of the F2 region and then to use it to specify a thickness parameter for the topside. This implies using some model relationship such as the one presented here.

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1. Barghausen, A.F., Finney, J.W., Proctor, L.L., and Schultz, L.D. (1969) Prediction Long-Term Operational Parameters of High-Frequency Sky-Wave Telecommunications Systems, ESSA Technical Report ERL 110-ITS-78.
2. The International Radio Consultative Committee (CCIR) (1970) Report No. 252-2, Documents of the XIIth Plenary Assembly, New Delhi (ITV, Geneva).

As a pilot study, a simple specification model has been constructed from profiles of the F region (1968-1971) kindly furnished by John Evans of Lincoln Laboratory. Results indicate that the mean topside thickness parameter can be estimated to within about 15 percent, assuming that the height of the F region is known, and that a useful reduction can be made in the day to day variability.

2. DEVELOPMENT OF A SIMPLIFIED MODEL

First define Q_c as the quarter thickness of a parabola[3] fit to the underside of the F2 region and define h_{max} as the height of the F2 maximum. Electron density profiles resulting from the reduction of bottomside vertical incidence ionograms such as those reported by Becker,[4] Clarke and Hammond,[5] and Wright[6] can be used to show that the mean noon and mean midnight values of Q_c vary with season and solar cycle in the same sense as the mean value of h_{max} (Figure 1).

Experimental profiles of the region above h_{max} are few and scattered. Available for this study were the archive profiles obtained from Evans which were produced by reduction of the incoherent scatter profiles from the Millstone Hill radar. About 151 days spanned the period July 1968 through December 1971 (about 3400 profiles edited).

A parabola was fitted both to the top and bottom of the individual profiles. Let us define Q_t as the parabolic quarter thickness for the topside segment between h_{max} and a higher height where the electron density equaled 0.7 of the density at the F2 peak. Similarly define Q_c for the bottomside segment between h_{max} and either the height whose density is 0.7 of the peak density or 200 km, whichever is greater.

The behavic of Q_t vs h_{max} is illustrated in Figure 2 for three time samples: day, night, and a transition period delimited by plus and minus two hours about ground sunrise and ground sunset. All observations from the 151 days are included. Count is given in each cell where size is 2 km in quarter thickness by 5 km in h_{max}.

The agreement of the variation of quarter thickness with h_{max} in Figures 1 and 2 suggests that an empirical model derived from the limited sample of incoherent scatter data might be useful over the wider latitude and time range of the data of Figure 1. If the data are considered in small blocks delimited by both time and season, then a linear relation such as

3. Piggott, W.R., and Rawer, K. (1972) URSI Handbook of Ionogram Interpretation and Reduction, 2nd ed., Report VAG-23.
4. Becker, W. (1970) The standard profile of the mid-latitude F region of the ionosphere as deduced from bottomside and topside ionograms, Space Research XII, Akademie Verlag, Berlin, 1241-1252
5. Clarke, C., and Hammond, E. (1965) J. Atmos Terr. Phys. 27:551.
6. Wright, J.W. (1962) J. Research Natl. Bur. Standards 66D:297.

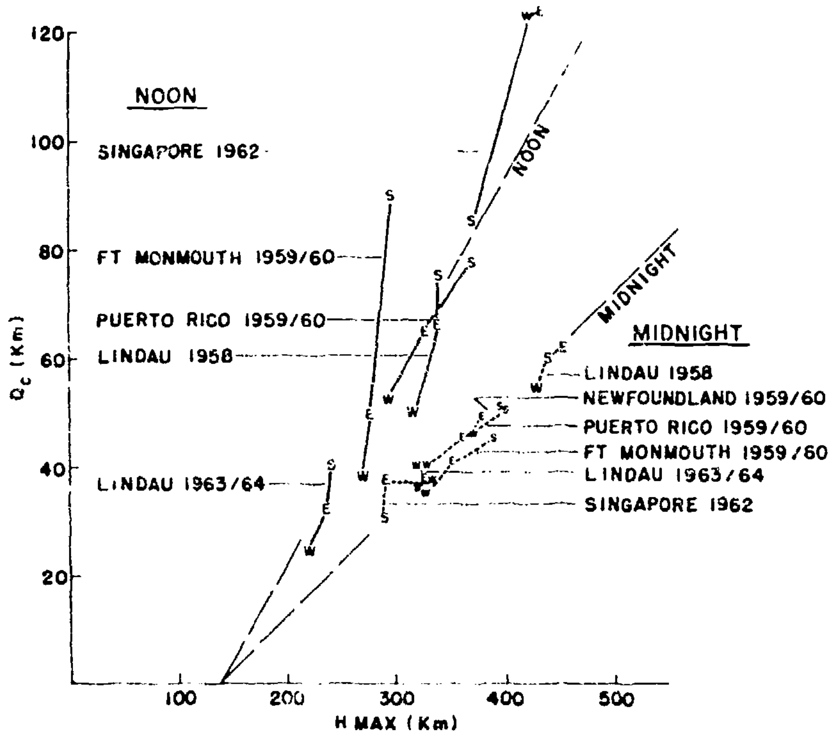

Figure 1. Parabolic Quarter Thickness of Bottom of F2 Region vs Height of Peak of F2 Region. Seasonal medians for several latitudes and for solar cycle extremes

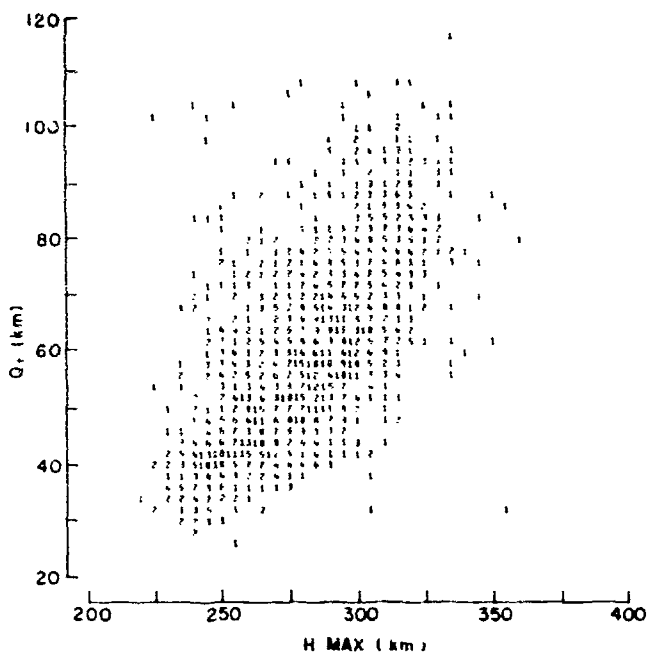

Figure 2a. Parabolic Quarter Thickness of Top of F2 Region vs Height of Peak of F2 Region. Individual observations from incoherent scatter at Millstone Hill: daytime

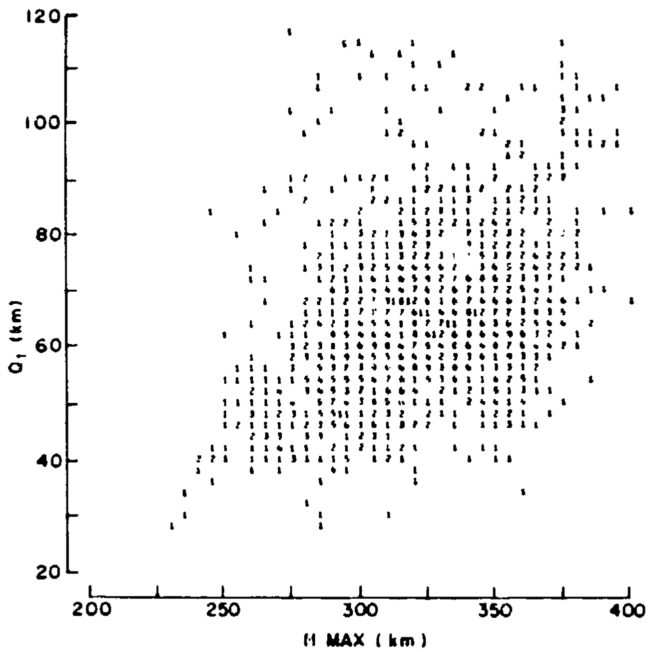

Figure 2b. Parabolic Quarter Thickness of Top of F2 Region vs Height of Peak of F2 Region. Individual observations from incoherent scatter at Millstone Hill: nighttime

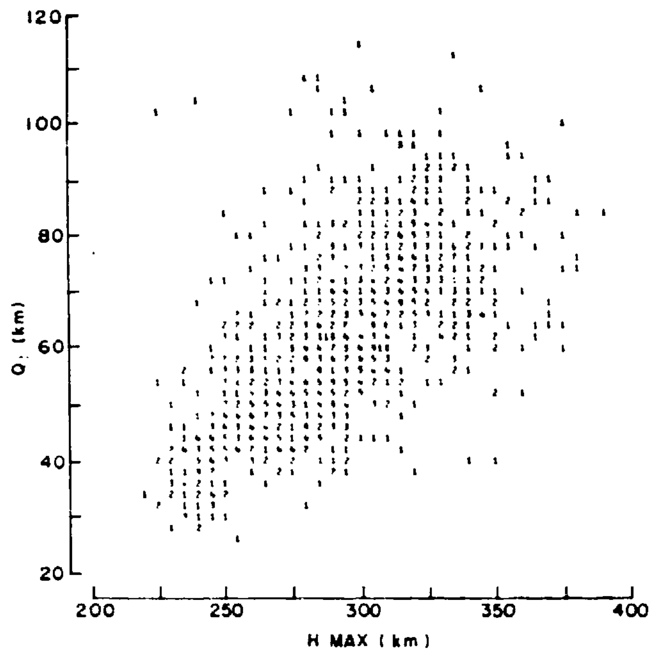

Figure 2c. Parabolic Quarter Thickness of Top of F2 Region vs Height of Peak of F2 Region. Individual observations from incoherent scatter at Millstone Hill: near sunrise and sunset

$$Q_t = k(h_{max} - 145) \tag{1}$$

is a simple engineering approximation. The choice of 145 km as reference point is arbitrary but consistent with both Figures 1 and 2.

To develop an empirical model around such a relationship, all the data were pooled and then the mean k of Eq. (1) was determined for cells of size month by hour. Results are contoured in Figure 3.

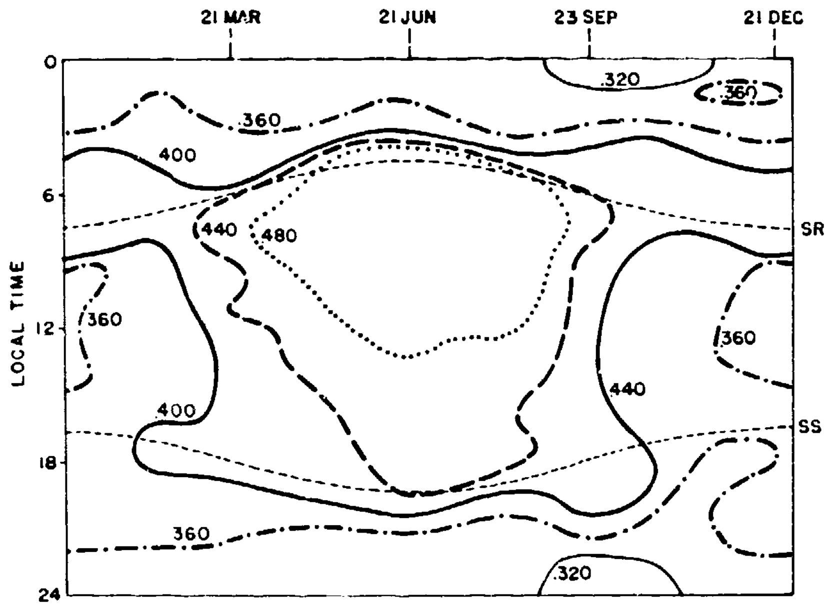

Figure 3. Seasonal-diurnal Variation of k from Eq. (1)

By inspection, the diurnal variation and the seasonal variation of k are not separable; consequently, the seasonal mean and the diurnal mean of the total sample are of no direct assistance in modeling the parameter. Becker[7] has already shown a dependence of Q_c on the mean solar flux (Φ) and the noon solar zenith angle (χ):

$$Q_c \propto \Phi \cos \chi$$

Unfortunately, the number of data points per month per year of this set is small, so in this paper Φ is assumed constant.

7. Becker, W. (1969) The seasonal anomaly of the F region at mid latitudes and its interpretation, in Electron Density Profiles in Ionosphere and Exosphere, Jon Frihagen, Ed., North Holland Publishing Company, Amsterdam, 218-230.

With this insight, a trial model discontinuous at sunrise (SR) and sunset (SS) was constructed such that the value of k in Eq. (1) was

$$k = 0.34$$

for the night hours (SS < t < SR), or (2)

$$k = 0.25\,(1 + \cos\chi)$$

for the day hours (SR $\leq$ t $\leq$ SS),

where t is local time. The difference between modeled k and the observed mean k is contoured in Figure 4. Background errors are generally less than 10 percent, while the worst errors are about 25 percent in summer and about 20 percent in winter.

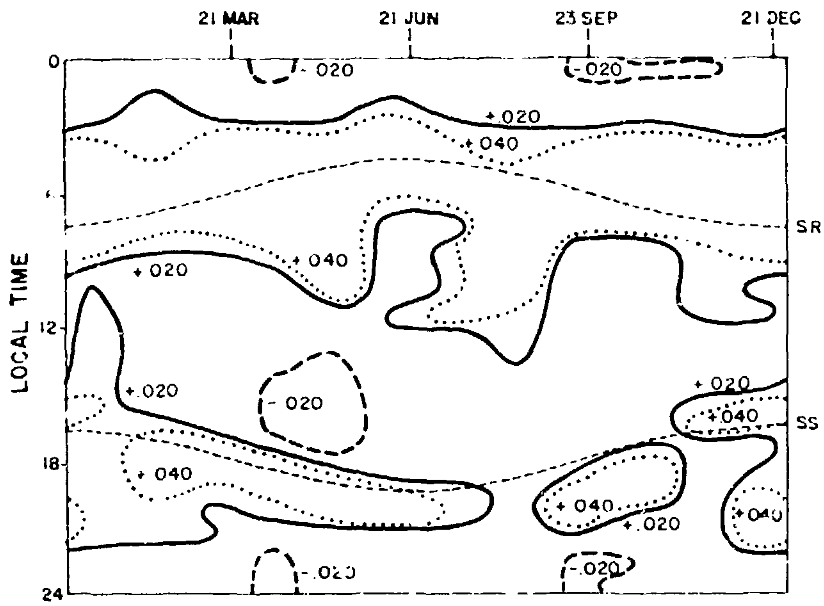

Figure 4. Difference Between Modeled k and Observed k for Eq. (2)

If empirical terms are added for the systematic variations in the transition periods near sunrise and sunset, then a relation such as

$$k = \frac{0.045}{\left(1 + (t - SS - 1)^4\right)} + \frac{0.090 \cos \chi}{\left(1 + \left(\frac{t - SR - 0.7}{2.3}\right)^4\right)} + \begin{cases} 0.34 & \text{if } SS < t < SR \\ 0.25(1 + \cos \chi) & \text{if } SR \le t \le SS \end{cases} \quad (3)$$

can model mean k with residual errors as shown in Figure 5.

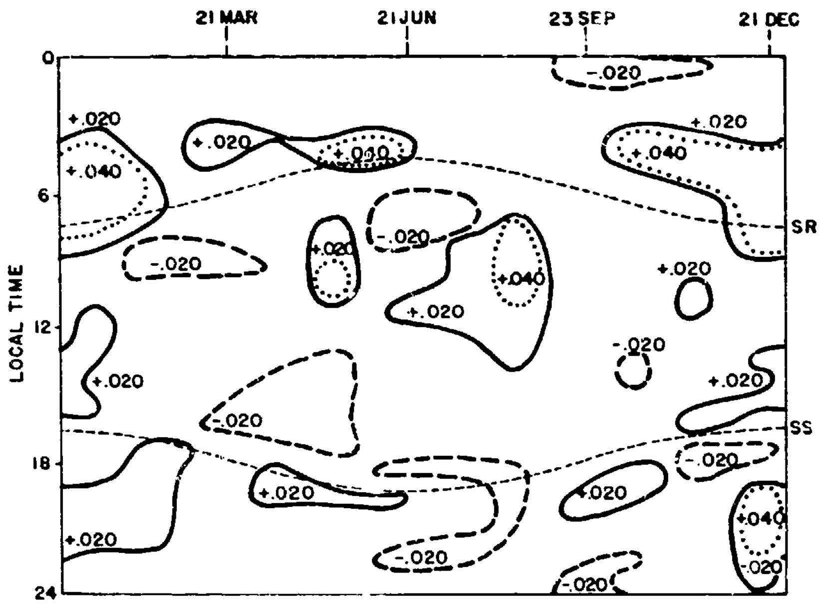

Figure 5. Residual Errors in Modeling k When Simple Terms are Added for Sunrise and Sunset as in Eq (3)

Inasmuch as it is proposed that this simple model be applied to other stations at higher and lower latitudes, as suggested by Figure 1, it would not seem proper to model the prominent features found during nighttime in winter and during the early day in summer, since they may well be local effects.

3. TEST

An estimate of the usefulness of the proposed model is made by testing it against the individual observations from which it was derived. As a test parameter, we use variability defined as the sum of the squares of the deviations between the observed values and predicted values.

For a first test, assume that some external climatology could provide, without bias, estimates of the mean value of the topside thickness for each of the samples of Figure 2. Then Table 1 shows that the specification model suggested here, using an accurate value of h_{max}, can provide individual estimates of topside thickness during the daytime with about 56 percent less variability than the variability about the sample mean. Note, however, that while the central value of the night sample has been specified usefully, the technique has not reduced the spread of individual values.

Table 1. Variability for Samples of Figure 2

	Sunrise to Sunset	Sunset to Sunrise	Sunrise ± 2 h Sunset ± 2 h
Sample size	1795	1608	1141
Average variability about sample mean	256	208	263
Average variability using model	112	187	134
Reduction of variability using model	56%	10%	49%

Consider a climatology that could provide mean values as a function of both month and time of day; then the variability might not be reduced as much as suggested by Table 1. To test against such a climatology, we divided the observations into cells 2 months by 2 hours (about 50 data points per cell). Linear regression relations for each cell were computed to approximate an efficient specification method. Results are shown in Table 2. The variability has been computed with reference to the mean value of each cell. During winter (Nov, Dec, Jan, Feb) and equinox (Mar, Apr, Sep, Oct) days, the simple model presented here is useful and not significantly inferior to the efficient relations derived from linear regression. As expected, the model fails significantly for summer mornings and winter nights, those periods where k of Eq. (3) was known to differ from the observations. It is of general interest to add that the low values of reduction of variability shown by the linear regression results for these same periods implies that the physical mechanism which correlates individual observations of h_{max} and Q_t is of negligible importance during these periods.

The technique should be verified with an independent source of data.

Table 2. Reduction of Variability for 2 month × 2 hour Samples*

Local Standard Time	Season											
	Winter				Equinox				Summer			
	Nov-Dec		Jan-Feb		Mar-Apr		Sep-Oct		May-June		July-Aug	
	R	M	R	M	R	M	R	M	R	M	R	M
00-02	.01	<.08>	.00	<.42>	.24	.16	.05	<.08>	.24	.19	.15	.05
02-04	.06	.00	.01	<.15>	.03	<.47>	.14	<.09>	.03	<1.30>	.19	.12
04-06	.03	<.31>	.00	<.54>	.40	.26	.31	.25	.04	<.57>	.17	.10
06-08	.47	.14	.48	.37	.11	.00	.17	<.01>	.06	<.60>	.26	.05
08-10	.50	.47	.41	.23	.16	.08	.14	<.05>	.00	<1.20>	.02	<.82>
10-12	.46	.43	.46	.25	.20	.19	.11	.16	.06	<.46>	.20	<.49>
12-14	.32	.30	.58	.39	.40	.40	.25	.22	.16	.04	.28	.24
14-16	.40	.34	.57	.36	.29	.28	.45	.42	.30	.29	.53	.53
16-18	.20	<.06>	.44	.41	.35	.32	.47	.43	.09	<.25>	.05	.02
18-20	.21	.10	.51	.41	.39	.17	.07	<.46>	.07	<.76	.17	.08
20-22	.13	<.07>	.36	<.15>	.08	<.37>	.00	<.24>	.04	<1.23>	.08	<.32>
22-24	.04	<.09>	.04	<1.08>	.16	.12	.00	<.40>	.43	.39	.32	.26

*First entry percentage reduction of the variability using linear regression (R) compared to sample mean; second entry percentage reduction or increase of variability using model (M) compared to sample mean. An increase is denoted by carets (<>).

4. DISCUSSION

From either climatology or a local measurement h_{max} is easily obtained; a thickness parameter is not. The useful correlation displayed between the two parameters over day, season, solar cycle and latitude recommends the use of a simple specification technique such as the one presented here. There are indications in both Figures 1 and 2 that a second order relation in h_{max} would be more exact, but unnecessary at this stage. In fact, to first order, Eq. (2) is sufficient since the improvement using the additional terms of Eq. (3) is only about 10 percent.

While this technique may be useful in modeling the upper ionosphere for various engineering applications, the significance of the basic physics contained in Eq. (1) is far from clear. The absence of appreciable diurnal or seasonal variation of the thickness of the lower E region is generally accepted, but note that the choice of 145 km as the null height of Eq. (1) was arbitrary and would be changed if a second order relation were substituted. On the other hand, it seems to be consistent with many observations that suggest the stability of atmospheric parameters in the vicinity of about 120 km.

Previous analysis of various models of the upper atmosphere suggests that the thickness parameter varies directly with the temperature of the electrons and ions and inversely with the force of gravity and the mean molecular mass. The variation of the force of gravity with height is a very small portion of the variation suggested by Figure 2; direct observations by satellite probes suggest that at the heights of interest, between 200 and 500 km, the mean molecular mass is very nearly that of 0^+. Therefore, the variation of the thickness of either the upper or lower F region is an expression of the effective ion-electron temperature. From this it is concluded that either the thickness or the height of the F region is a macroparametric measure of the temperature.

The change of thickness parameter with the day to day change of solar or geophysical activity is considered a promising separate study.

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2. The International Radio Consultative Committee (CCIR) (1970) Report No. 252-2 Documents of the XIIth Plenary Assembly, New Delhi (ITV, Geneva).
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